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THE MEASUREMENT OF LARGE WIND ENERGY GENERATORS

C. Martini

Translation of "Ueber die Bemessung von Grosswindkraftgeneratoren," Elektrotechnik und Maschinenbau, Vol. 57, No. 7/8 February 17, 1939, pp. 83-89.

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16. Abstract

The weight comparison of energy generators according to the Honnef System is represented in curves wherein the weight is plotted as a function of three variables: the number of poles, air induction, and diameter.

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THE MEASUREMENT OF LARGE WIND ENERGY GENERATORS

C. Martini[1]

Our economy's continuously increasing demand for energy, our declining coal /83*
reserves, the use of coal as a raw material, and efforts to become independent of imported energy compel us to look for new energy sources. One source is represented by wind energy, though it finds neglible use today and remains practically completely unexploited relative to its potential. Of the schemes known today for exploiting wind energy, one of the most noteworthy is that of engineer Hermann Honnef. In a book published in 1932 by Bieweg Publishing, Brunswick, Honnef explained the basic features of large scale wind energy expoitation. A system of three to five wind wheels is mounted on towers about 300 m high. Each wheel is able to deliver up to 200,000 kW power. Such a wind wheel consists of two counter-rotating fan wheels, with vane diameter 120 - 160 m, one bearing a polar ring and the other a generator armature ring. This arrangement eliminates gears in transforming kinetic energy to electrical energy. The novel problems arising for the electrical engineer will be discussed in greater detail below, with regard to generator dimensions. Favorable conditions for pole number, air induction, and diameter will be investigated.

The task is fundamentally different from usual ones, in that the choice of pole number and of voltage is open within certain limits. The given data are:

D_1 = Vane diameter of rear wheel
D_2 = Vane diameter of front wheel
v = Wind velocity
u_1 = Vane tip velocity of rear wheel
u_2 = Vane tip velocity of front wheel

The blades of both wheels are aerodynamically designed such that maximum efficiency is obtained when $j/v = 6$, i.e., when the blade tip velocity is equal

[1]Falkensee/Berlin

*Numbers in margin indicate pagination from foreign text.

to 6 times the wind velocity. Assuming a generator efficiency of 87.5 vH, with a wind velocity of 15m/sec, the generator produces 17,500 KW. If we write the power factor as equal to 1 (which can easily be achieved with presently available means), the interlinked terminal voltage for a 7200 V AC generator proves to be $\frac{175.10^5}{\sqrt{3}.72.10^2}$ = 1405 A. This requires a conductor cross section of 400 mm^2 for a current density of about 3.5 A/mm^2 with only one armature circuit. We will now set the groove pitch as approximately 3.5 cm and, in order to avoid overly high tooth induction, neighboring grooves will be staggered with respect to one another and designed as circular conduction grooves (Figure 1). The groove pitch is $\tau = \frac{\pi . d}{N}$, where d denotes the armature diamter and N the total number of grooves. The number of grooves per pole N/2p must be divisible by 3 for alternating current. The length and number of armature wires per phase, necessary for a given voltage, can be derived from the induction law:

$$(E = B.l.v.10^{-8}\,V) \qquad z/Ph = \frac{\sqrt{2}\,E_v.10^8}{\sqrt{3}.B_l.l_E.v_r.0{,}96} \qquad (1)$$

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where E_v = the interlinked EMF in volts,

$\sqrt{2}$ = amplitude factor

B_1 = air induction

1_E = pure actual iron length of the armature in cm

v_r = relative velocity between armature and pole ring in cm/sec.

0.96 = estimated space factor.

We refrain from inserting the ideal armature length in place of the pure iron length, since the two values are only slightly different in machines without radial tolerance, and in the preliminary design the space factor and EMF are only estimated.

If we arrange Equation (1) according to 1_E and introduce $\tau N = \frac{\pi . d}{N}$ on the right side, we obtain

$$l_E = \frac{\sqrt{2}}{\sqrt{3}} \cdot \frac{E_v\,\tau_N.N.10^8}{B_l.v_r.\pi d.z.0{,}96} \qquad (2)$$

By multiplying numerator and denominator by 3, we get the factor N/3x, which represents the reciprocal of the number of wires per groove. This is set equal to 1. Through the counter-rotation of the wheels, we have

$$v_r = \frac{u_1 \cdot d}{D_1} + \frac{u_2 \cdot d}{D_2}$$

and since $u_1 = u_2 = 6v$,

$$v_r = 6v \cdot d \cdot \left(\frac{1}{D_1} + \frac{1}{D_2}\right)$$

and thus

$$l_E = \frac{\sqrt{2}}{\sqrt{3}} \cdot \frac{E_v \cdot \tau_N \cdot 3 \cdot 10^8}{\mathfrak{B}_l \cdot \pi \cdot d \cdot 0{,}96 \cdot 6v \cdot d \cdot \left(\frac{1}{D_1} + \frac{1}{D_2}\right)} \cdot \frac{N}{3}$$

This expression asserts that the armature length, at constant induction, voltage, and groove pitch, varies inversely with the square of the diameter. This can be seen immediately, since both the number of wires and the perimeter velocity vary in proportion to diameter.

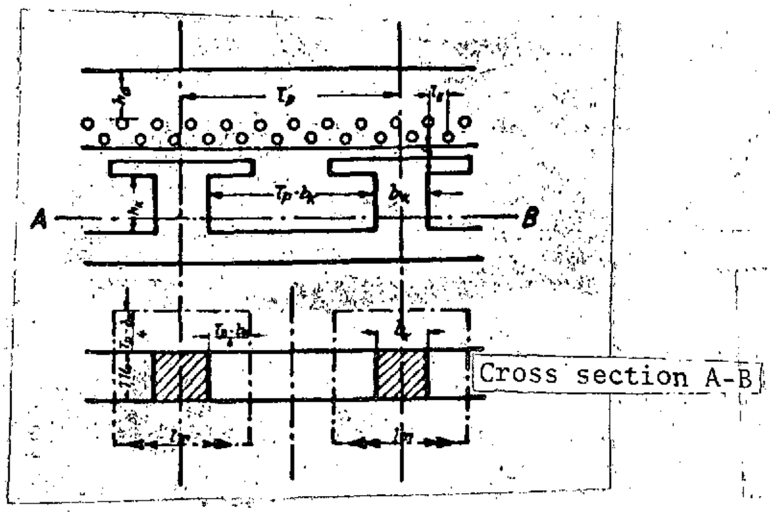


Figure 1.

In establishing a generator diameter, the decisive points from the electrical engineer's viewpoint are weight and efficiency. In addition, however, the requirement of the stress analyst must be taken into account. It is imaginable, for example, that the diameter favorable for the electrical engineer produces unfavorable stresses on the vanes, from the stress analyst's viewpoint. The ideal solution can thus only be reached by both parties working together. In view of the large opportunity for variation is such a design, a suitable procedure appears to be a comparative investigation of weight relationships, to form an idea of how the variables (diameter, air induction, and pole number) are to be chosen. It is obvious that assumptions must be made in such an investigation, which are in practice never exact. But since these are made generally, the relative proportions change only slightly, and with a detailed calculation of the chosen type, a deviation in absolute weight of a few percent at most can result.

Let the generator power output be 17,5000 kW, $\cos \phi = 1$,

D_1 = 160 m.

D_2 = 120 m.

v = 15m/sec.

$u_1 = u_2 = 6v = 90$m/sec,

τN = 3.5 cm.

U_v = 7200 V.

E_v = 7800 V assumed

$\frac{3z}{N}$ = No. of wires per groove = 1.

a = the number of parallel armature windings.

With these data, the axial iron length is

$$l_E = \frac{\sqrt{2}}{\sqrt{3}} \frac{7800 \cdot 3{,}5 \cdot 3 \cdot 10^9 \cdot a}{\mathfrak{B}_l \cdot 0{,}96 \; \pi d^2 \; 9000 \left(\frac{1}{16000} + \frac{1}{12000}\right)} = \frac{1{,}687 \cdot 10^{11} \cdot a}{d^2 \cdot \mathfrak{B}_l}$$

and the number of wires per phase is

$$z/Ph = \frac{\pi d}{3 \cdot \tau_N} = 0{,}3\, d.$$

In this way, we get as a function of diameter, the following values for the number of wires per phase and with various inductions for the iron length in cm:

TABLE 1

	l_E			
d_m	$\mathfrak{B}_l$ = 8600	6300	4000	z/Ph
10	196	267,5	421	300
20	49	66,9	105,5	600
30	21,8	29,75	46,9	900
40	12,25	16,7	26,3	1200
50	7,84	10,7	16,85	1500
60	5,44	7,42	11,7	1800
70	4,0	5,46	8,6	2100
80	3,06	4,17	6,58	2400

NOTE: Commas indicate decimal points.

Here a is set equal to one.

The armature height h_a over the teeth, with a given armature induction, proves to be a function of air induction, B_l: $h_a = \frac{\mathfrak{B}_l}{\mathfrak{B}_a} \cdot \frac{\tau_p}{3}$, where it is presupposed that the induction in the air gap extends over 2/3 of the pole pitch. /85
By multiplying h_a by τp, we obtained the armature face surface of a pole pitch, as $F_{A/P} = \frac{\mathfrak{B}_l}{3\mathfrak{B}_a} \cdot \tau_p^2$. There is an additional factor for the tooth surface and the groove height be 8 cm and the ratio between the tooth surface and the groove surface by 7:3. The tooth surface of a pole pitch is then

$$8 \cdot 0{,}7 \cdot \tau_p = 5{,}6 \cdot \tau_p \text{ cm}^2.$$

The iron weight of the field spider is composed of yoke, core, and pole shoe weight. The yoke height is given by taking as a basis an induction ratio between yoke and core of 5.5 to 6 to 0.5 b_k. 6/5.5 = 0.54 b_k, where b_k signifies the pole core width (Figure 1). The pole shoes cover 2/3 of the pole pitch and are 3 cm high. Their slope is not taken into account, and for this reason the factor 1.1 when multiplied by l_E, is omitted. The pole shoe surface thus amounts to . For the entire iron weight we accordingly get the following expression:

$$G_E = \Big(\overbrace{1{,}1\, h_k \cdot b_k}^{\text{Pole Core}} + \overbrace{1{,}1 \cdot 0{,}54 \cdot b_k \cdot \tau_p}^{\text{Yoke}} + \overbrace{\frac{\mathfrak{B}_l}{3\mathfrak{B}_a} \cdot \tau_p^2}^{\text{Armature}} + \overbrace{(5{,}6 + 2)\,\tau_p}^{\text{Teeth \& Pole Shoe}}\Big) \cdot 2p \cdot l_E \cdot 7{,}8 \cdot 10^{-3}\,\text{kg} \qquad (3)$$

Calculation of the pole core width b_k and pole core height h_k results from the following considerations:

With a given induction (e.g., 17,500), the pole core diameter must be dimensioned for the total flux, i.e., the stray flux plus the useful flux. The stray flux is dependent on the distance between the poles, i.e., the distance between the cores and shoes, and on the height of the pole cores and shoes. The core dimensions must be chosen such that the aperture cross section leaves enough space for accomodating the magnet winding. The following assumptions are made: the pole core flux is directly proportional to half the pole core height and inversely proportional to the distance between pole core sides[2]. The pole core stray flux on one side of the core is

$$\Phi_{ko} = I \cdot w \cdot \Lambda = I \cdot w \cdot 0{,}4\pi \frac{h_k}{2} \cdot \frac{1{,}1\, l_E}{\tau_p - b_k}.$$

[2]Compare Thomaelen, Kurzes Lehrbuch der Elektrotechnik (A Brief Textbook of Electrotechnology), 9th edition, page 50.

The pole shoe stray flux is proportional to the pole shoe height and inversely proportional to the distance between two pole shoe edges.

$$\Phi_{schs} = i \,.\, w \,.\, 0{,}4\,\pi \cdot \frac{3 \,.\, 1{,}1\, l_E}{\tau_p/3}$$

This pole shoe stray flux is really somewhat smaller, since the mutual slope of the pole shoes is not taken into account in the calculation. For this reason, the stray flux for the teeth is not discussed below. The entire stray flux inside one pole pitch is

$$\Phi_{ks} + \Phi_{schs} = i \,.\, w \,.\, 0{,}4\,\pi \,.\, 1{,}1\, l_E \left(\frac{h_k}{2} \cdot \frac{1}{\tau_p - b_k} + \frac{9}{\tau_p} \right).$$

Here the frontal stray flux is neglected. The associated useful flux per pole pitch is

$$\Phi_N = \mathfrak{B}_l \cdot \frac{\tau_p}{3} \cdot l_E.$$

The aperture cross section required for 100 ampereturns amounts to 1 cm^2. This value is chosen such that only ampere turns for the air gap need be taken into account in the calculation. With the air core sizes involved here, its value is disproportionally high compared to iron. The A.T. amounts to $i \,.\, w_L = 1{,}6\, \mathfrak{B}_l \,.\, \delta$. According to the above assumption, the space required for this amounts to

$$\frac{1{,}6\, \mathfrak{B}_l \,.\, \delta}{100} = h_k \,.\, (\tau_p - b_k),$$

where δ denotes the air gap. This is to be regarded as a function of the diameter, since, for mechanical reasons, it must increase as the diameter increases. This can be allowed for by using the formula

$$\delta_{cm} = \frac{d_{cm}}{4000} + 1$$

An air-cooled arrangement is supposed for the magnetic winding, where the bare wires are supported by a mounting device and spacer. We then have:

$$h_k = \frac{1{,}6\, \mathfrak{B}_l \,.\, \delta \,.\, 10^{-2}}{\tau_p - b_k} \quad \text{oder} \quad b_k = \tau_p - \frac{1{,}6\, \mathfrak{B}_l \,.\, \delta \,.\, 10^{-2}}{h_k}. \tag{4}$$

Thus, the stray flux becomes

$$\Phi_{str} = 100\, h_k \,.\, (\tau_p - b_k) \,.\, 0{,}4\,\pi \,.\, 1{,}1\, l_E \left(\frac{h_k}{2} \cdot \frac{1}{\tau_p - b_k} + \frac{9}{\tau_p} \right).$$

and the useful flux

$$\Phi_N = 100 h_k (\tau_p - b_k) \cdot \frac{0{,}4\pi \cdot \tau_p \cdot l_E}{6\delta};$$

$$\Phi_N + \Phi_{str} = 40\pi \cdot h_k \cdot (\tau_p - b_k) \cdot l_E \times$$
$$\times \left(\frac{\tau_p}{6\delta} + \frac{h_k}{2} \cdot \frac{1{,}1}{\tau_p - b_k} + \frac{1{,}1 \cdot 9}{\tau_p}\right);$$

$$2 \cdot (\Phi_N + \Phi_{str}) = 80\pi \cdot h_k \frac{1{,}6\,\mathfrak{B}_l \cdot \delta \cdot 10^{-8}}{h_k} \times$$
$$\times l_E \left(\frac{\tau_p}{6\delta} + \frac{h_k}{2} \cdot \frac{1{,}1\,h_k}{1{,}6\,\mathfrak{B}_l \cdot \delta \cdot 10^{-8}} + \frac{9{,}9}{\tau_p}\right) =$$
$$= \mathfrak{B}_k \cdot 1{,}1\, l_E \cdot b_k =$$

= pole core induction x core cross section.

Thus;

$$\mathfrak{B}_k = \frac{80\pi \cdot 1{,}6\,\mathfrak{B}_l \cdot \delta \cdot 10^{-8}}{1{,}1\, b_k} \left(\frac{\tau_p}{6\delta} + \right.$$
$$\left. + \frac{h_k}{2} \cdot \frac{1{,}1\,h_k}{1{,}6\,\mathfrak{B}_l \cdot \delta \cdot 10^{-8}} + \frac{9{,}9}{\tau_p}\right).$$

Finally one obtains:

$$125{,}6\, h_k^3 + 0{,}609\,\mathfrak{B}_l \cdot \tau_p \cdot h_k + 36{,}2\, h_k \mathfrak{B}_l \cdot \frac{\delta}{\tau_p} +$$
$$+ 1{,}6 \cdot 10^{-8}\,\mathfrak{B}_l \cdot \mathfrak{B}_k \cdot \delta - \mathfrak{B}_k \cdot \tau_p \cdot h_k = 0. \qquad (5)$$

With the aid of these third order equations for h_k, the required core height h_k can be determined for fixed B_l, B_k, τp and δ. Thus core width can be thereby determined from Equation (4). From Equation (3) for the iron weight, it can be seen, upon substitution $\pi d/2p$ for τ_p, that the iron weight, relative to pole number, is composed of three components: /86

1. of a value that is independent of pole number, and that represents tooth and pole shoe weight,

2. of a value proportional to pole number, which represents core weight,

3. of a value, inversely proportional to the pole number, which represents the armature iron weight.

The proportionality of the core weight is non-linear, since the quantities h_k and B_k are themselves dependent on pole pitch and pole number [Equations (4) and (5)]. But it can immediately be seen that increasing the pole number increases the stray flux, if only through the lessened distance between pole cores and shoes. This causes an increase in core width, which again reduces core separations, and furthermore reduces the aperture cross section required for the magnet winding. This must again be equalized by enlarging the pole core height. As a consequence, the stray flux increases again. The maximum possible pole number is situated where the requirement for aperture cross section can no longer be met, even though the core height is enlarged, because the increased stray flux increases the associated core width. This occurs where enlargement of core height no longer permits a reduction in pole pitch, i.e., where $d\tau p/dh_k = 0$. The weight minimum, however, lies at a lower pole number as is shown by differentiation of the iron weight with respect to the number of pole pairs. B_1 and d are here taken as constant, but the partial differentiation with respect to h_k and b_k must be performed. Then

$$\boxed{\frac{dG_E}{dp} = \frac{\partial G_E}{\partial h_k}\frac{dh_k}{dp} + \frac{\partial G_E}{\partial b_k}\frac{dh_k}{dp} + \frac{\partial G_E}{\partial p}}$$

The derivative dh_k/dp is to be formed from (5), db_k/dp from Equation (4) where it must be noted that

$$\boxed{\frac{db_k}{dp} = \frac{\partial b_k}{\partial h_k}\frac{dh_k}{dp} + \frac{\partial b_k}{\partial p}}$$

for the differentiation with respect to number of pole pairs, there results:

$$\boxed{\begin{aligned}\frac{dG_E}{dp} = \Bigg[& 1{,}1\, b_k \cdot 2p\, \frac{0{,}609\, \mathfrak{B}_l \cdot h_k \cdot \frac{\pi d}{2p^2} - 36{,}2\, h_k \cdot \mathfrak{B}_l \cdot \delta \cdot \frac{2}{\pi \cdot d} - \frac{\mathfrak{B}_k \cdot h_k \cdot \pi \cdot d}{2p^2}}{0{,}609\, \mathfrak{B}_l \cdot \frac{\pi d}{2p} + 376{,}8 \cdot h_k^2 + 36{,}2\, \mathfrak{B}_l \cdot \delta \cdot \frac{2p}{\pi d} - \mathfrak{B}_k \frac{\pi \cdot d}{2p}} + \\ & + (1{,}1\, h_k \cdot 2p + 0{,}6\, \pi d) \cdot \left(\frac{0{,}609\, \mathfrak{B}_l \cdot h_k \cdot \frac{\pi d}{2p^2} \ldots}{0{,}609\, \mathfrak{B}_l \cdot \frac{\pi d}{2p} + \ldots} \frac{\pi d}{2p^2} \right) + 2{,}2\, h_k \cdot b_k - \frac{\mathfrak{B}_l \cdot \pi^2 \cdot d^2}{6\, \mathfrak{B}_a \cdot p^2} \Bigg] l_E \cdot 7{,}8 \cdot 10^{-6}\end{aligned}}$$

Figure 2 shows iron weight as a function of pole number, for two parallel current circuits, i.e., for a 60 m generator diameter and for air inductions of 8600, 6300, and 4000 gauss. The weight minima lie below the maximum number of poles. The latter increases as induction decreases. For 8600, the maximum possible pole number lies between 600 and 700. As can be seen from the curves, the high induction of 8600 affords no saving of iron compared to the induction 6300. But it requires, as will be shown later, a disproportionately high expenditure of magnet winding copper. It is therefore out of the question in choosing induction. /87

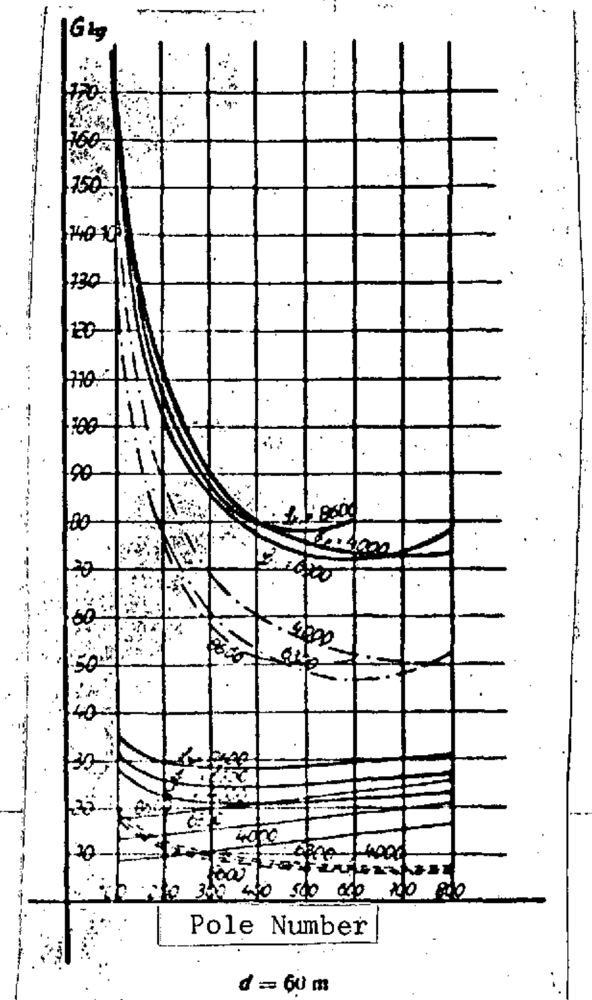


Figure 2

Curve Designations

Iron plus copper weight

Iron weight

Total copper weight

Armature winding weight

Magnet winding weight

The iron weight for a diameter of 60 meters is plotted in Figure 3 for 300 and 600 poles, as a function of induction. It can be seen from these curves that the saving in iron becomes smaller and smaller with increasing induction. For 2p = 600, the minimum lies between 6000 and 7000 gauss. Above this lies the range of maximum possible induction, which naturally is at a lower level for high pole number than for lower pole number. By similarly applying the above formula, we obtain for the derivation: /88

$$\frac{d G_E}{d \mathfrak{B}_l} = \Bigg[1{,}1 b_k \cdot \frac{-0{,}609 \tau_p . h_k - 36{,}2 h_k \cdot \frac{\delta}{\tau_p} - 1{,}6 . 10^{-8} \mathfrak{B}_k . \delta}{0{,}609 \mathfrak{B}_l . \tau_p + 376{,}8 h_k^2 + 36{,}2 \mathfrak{B}_l \frac{\delta}{\tau_p} - \mathfrak{B}_k . \tau_p} + (1{,}1 h_k + 0{,}6 \tau_p) . \left(\frac{1{,}6 \mathfrak{B}_l . \delta . 10^{-8}}{h_k^2} \cdot \frac{-0{,}609 \tau_p . h_k - \ldots}{0{,}609 \mathfrak{B}_l . \tau_p + \ldots} - \frac{1{,}6 \delta . 10^{-8}}{h_k} \right) + \frac{\tau_p^2}{3 \mathfrak{B}_a} - \frac{1}{\mathfrak{B}_l} \cdot \left(1{,}1 h_k . b_k + 0{,}6 b_k . \tau_p + \frac{\mathfrak{B}_l}{3 \mathfrak{B}_a} \cdot \tau_p^3 + 7{,}6 \tau_p \right) \Bigg] . 2p \cdot \frac{1{,}687 . 10^{12} . a}{d^2 . \mathfrak{B}_l} \cdot 7{,}8 . 10^{-3}.$$

For 300 poles with about 57,500 kg, the iron weight has a minimum between 11,000 and 12,000 gauss.

The same consideration apply also to the diameter. We have

$$\frac{d G_E}{d d} = \Bigg[1{,}1 b_k \cdot \frac{-0{,}609 \mathfrak{B}_l . h_k \cdot \frac{\pi}{2p} + 36{,}2 \mathfrak{B}_l . h_k \frac{2p}{\pi d^2} - \frac{1{,}6 . 10^{-8}}{4000} \mathfrak{B}_l . \mathfrak{B}_k + \mathfrak{B}_k . h_k \frac{\pi}{2p}}{0{,}609 \mathfrak{B}_l \cdot \frac{\pi d}{2p} + 376{,}8 h_k^2 + 36{,}2 \mathfrak{B}_l . \delta \cdot \frac{2p}{\pi d} - \mathfrak{B}_k \cdot \frac{\pi d}{2p}} + \left(1{,}1 h_k + 0{,}6 \frac{\pi d}{2p} \right) . \left(\frac{1{,}6 \mathfrak{B}_l . \delta . 10^{-8}}{h_k^2} \cdot \frac{-0{,}609 \mathfrak{B}_l . h_k \cdot \frac{\pi}{2p} + \ldots}{0{,}609 \mathfrak{B}_l \cdot \frac{\pi d}{2p} + \ldots} + \frac{\pi}{2p} - \frac{1{,}6 \mathfrak{B}_l . 10^{-8}}{4000 h_k} \right) + \frac{1{,}1 h_k . h_k}{d} - 0{,}6 b_k \cdot \frac{\pi}{2p} - \frac{7{,}6 \pi}{2p} \Bigg] . \frac{2p . 1{,}687 . 10^{11} . a}{\mathfrak{B}_l . d^2} \cdot 7{,}8 . 10^{-3}.$$

The iron weight declines with increasing diameter (Figure 4). For very large diameters, iron lengths of only a few centimeters are encountered, which makes copper utilization uneconomically large.

The copper weight consists of two parts: magnet winding copper and armature winding copper. For the first, the following formula is valid, assuming that the available winding space is homogeneously filled:

$$\boxed{G_{Cu\,MW} = \frac{0{,}8 \mathfrak{B}_l . \delta}{i} . (2{,}2 l_E + 2 \tau_p) . 2p . 8{,}9 . 10^{-3} \text{kg}}$$

Here, i denotes current density in A/cm^2. The first factor represents the wire cross section, assuming only one winding per pole. We have 0.8 B_1 δ/i = i.w, and since i = Q·i, 0.8B_1·δ/i=Q, where Q is the wire cross section. The expression in parentheses represents the mean winding length, and can be read from Figure 1 (Section A...B). This is based on a rectangular pole core cross section.

The armature winding copper is obtained from

$$G_{CuAW} = (40 + \tau_p + 1{,}1\, l_E) \,.\, 3\, z \,.\, q \,.\, 8{,}9 \,.\, 10^{-3}\,\mathrm{kg}.$$

Here the mean distance of the frontal connection from the armature iron is assumed to be 20 cm long, and q is the conductor cross section. Using this formula, curves can also be drawn for the copper weight, exactly as with the iron weight. Figures 2, 3, 4 show relationships similar to those for iron. Here the value $i = 3.5\ \mathrm{A/mm^2}$ is assumed for the current density in the magnet winding. The derivatives with respect to the three variables are as follows:

$$\frac{d\,G_{Cu}}{d\,p} = \frac{2{,}97 \,.\, \delta \,.\, 10^{11} \,.\, a}{d^2} \cdot \frac{2}{i} \cdot 8{,}9 \,.\, 10^{-3} + \frac{\pi^2 \,.\, d^2}{2 p^2 \,.\, \tau_N} \cdot q \,.\, 8{,}9 \,.\, 10^{-3}.$$

The position of the minimum is independent of induction, for the relevant circumstances with about 186 pole pairs:

$$\frac{d\,G_{Cu}}{d\,\mathfrak{B}_l} = \left(\frac{1{,}6 \,.\, \delta \,.\, \pi \,.\, d}{i} - \frac{1{,}855 \,.\, a \,.\, 10^{12} \,.\, \pi \,.\, q}{\mathfrak{B}_l^2 \,.\, d \,.\, \tau_N} \right) . \, 8{,}9 \,.\, 10^{-3}.$$

The minimum for a 60 m diameter lies at an induction of 2000 gauss, independent of pole number:

$$\begin{aligned} \frac{d\,G_{Cu}}{d\,d} = \Bigg[\left(\frac{d}{4000} + 2 \right) \cdot \frac{2{,}97 \,.\, 10^{11} \,.\, a \,.\, 2p}{d^3 \,.\, i} &+ \\ + \frac{1{,}6\, \mathfrak{B}_l \,.\, \pi \,.\, 2d}{4000\, i} + 1{,}6\, \mathfrak{B}_l \cdot \frac{\pi}{i} + \frac{40\, \pi \,.\, q}{\tau_N} &+ \\ + \frac{\pi^2 \,.\, q \,.\, d}{p \,.\, \tau_N} - \frac{1{,}855 \,.\, a \,.\, 10^{11} \,.\, \pi \,.\, q}{\mathfrak{B}_l \,.\, d^2 \,.\, \tau_N} \Bigg] &. \, 8{,}9 \,.\, 10^{-3}. \end{aligned}$$

The minimum, for an induction of 6300 gauss and 150 pole pairs, lies at a diameter of about 34.7 m.

All curves of Figures 2, 3, and r are valid for the arrangement of two parallel current circuits, and with an armature wire cross section of 160 $\mathrm{mm^2}$. By means of these formulas, and of the corresponding ones for iron weight, it is possible to determine the minimum for the total weight, for assumed circumstances. To determine the absolute minimum, that is, of those quantities p, B_1. d for which the least total weight results, and system of equations

$$\frac{d\,(G_E + G_{Cu})}{d\,p} = 0, \quad \frac{d\,(G_E + G_{Cu})}{d\,\mathfrak{B}_l} = 0,$$

$$\frac{d\,(G_E + G_{Cu})}{d\,d} = 0$$

and Equations (4) and (5) for both b_k and h_k must be utilized. The solution can be approximated, by taking values from the plotted curves (for example, 2p = 560, B_1 = 6000, d = 55 m), and then determining the deviations from 0 of the system of equations.

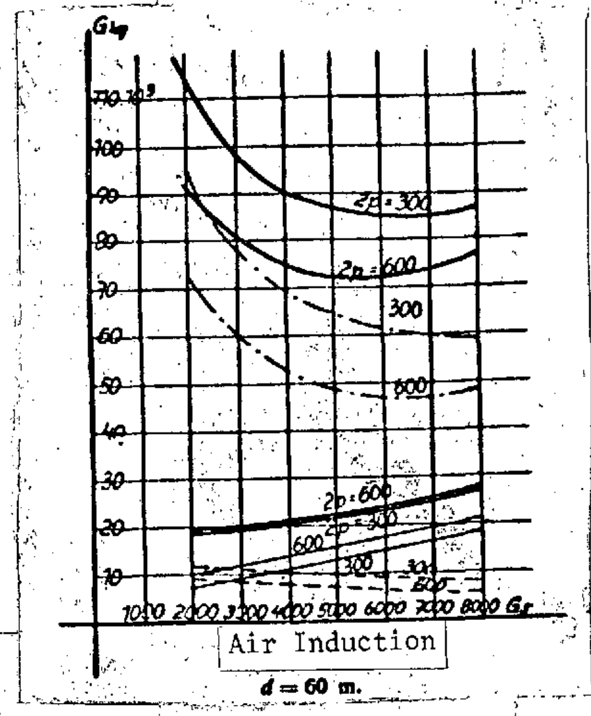


Figure 3.

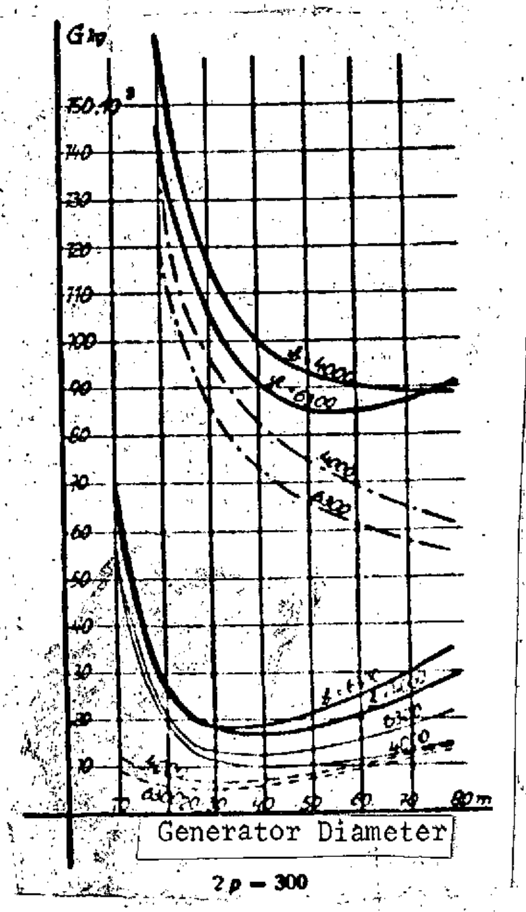
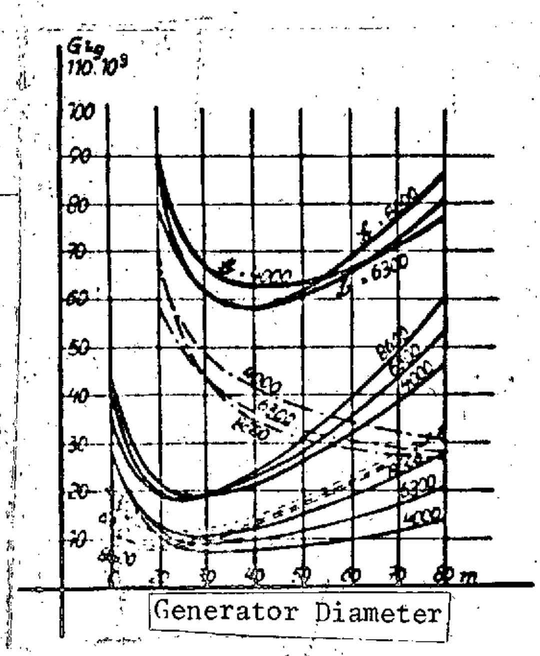


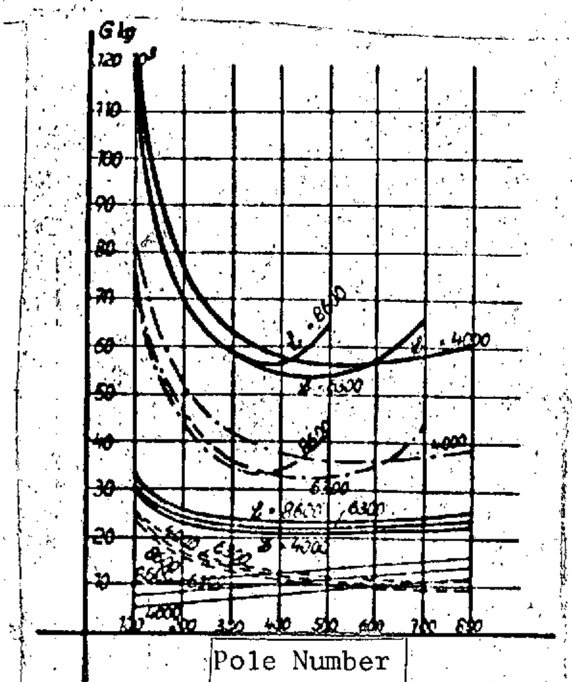
Figure 4.

We can now ask whether it makes sense to choose these approximately determined minimum values for the final design. One glance at the curves shows that the minima are quite flat within certain limits. Where the curves consist of a portion which falls (iron weight) and of a portion which rises (copper weight) in just about the same amount, the iron weight should be increased in favor of copper weight, if there are no opposing reasons. Thus, for example, Figure 4 shows that by reducing the diameter from 55 to 50 m, a saving of about 2000 kg copper counterposes an added expenditure of about 2600 kg iron.

The calculations are based on a fixed groove pitch and on a fixed actual armature length, according to Table 1 and Equation (2). For this reason, the values shown in the curves do not always give the most favorable relationship of iron to copper. But use of the curves makes it easy to determine the relationships for other actual iron lengths or groove pitches or armature wire numbers. To do this, an increase in armature iron length must be counterposed by a corresponding reduction in armature wire number. Thus, for example, in Figure 4, at a diameter of 80 m, doubling the actual length would correspond to an increase in iron weight from 55 t to 110 t. This would be counterposed by a reduction of copper weight from about 13 t to 6.5 t. Here, the small increase in magnetic winding weight and armature winding weight which results from enlarging the actual length, has not yet been taken into consideration. A total weight increases from 80 t to about 130 t could be estimated here. An increase of total weight will always occur when actual length is increased, in those cases where the iron weight is greater than the armature winding weight. /89



2p = 300, one current
Figure 5.



d = 40 m, one current
Figure 6.

For comparison with a design having two parallel current circuits, Figures 5 and 6 show the weight relationships as a function of diameter and pole number for the design with only one current circuit. The armature wire cross section has here been raised from 160 mm^2 to 400 mm^2. The curves show that for smaller diameters and pole numbers, considerable weight savings are possible. A minimum of about 54,000 kg can, for example, be read off at 450 poles, and 40 m diameter, at an air induction of 6300 gauss. The saving is here made principally on iron weight. Copper weight, in both cases, lies between 20,000 and 25,000 kg. The single circuit design should therefore be preferred, if the stress analyst's considerations do not rule out a smaller diameter.

Summary:

The weight comparison of large wind energy generators for large wind wheels of 160/120 m vane diameter, with about 20,000 kW power, at a wind velocity of 15 m/sec, gives favorable diameter values between 40 and 60 m, pole numbers between 300 and 600, and air inductions about 6000 gauss. In determining these values, for example that of the diameter, whose choice is not entirely arbitrary when static factors are considered, it is easily possible to determine the other variables so as to obtain a minimum weight or an optimum weight ratio of copper to iron.

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